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## H<sub>2</sub>-bearing damped Lyman- $\alpha$ systems as tracers of cosmological chemical evolution

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### Abstract.

The chemical abundances in damped Lyman- $\alpha$  systems (DLAs) show more than 2 orders of magnitude variation at a given epoch, possibly because DLAs arise in a wide variety of host galaxies. This could significantly bias estimates of chemical evolution. We explore the possibility that DLAs in which H<sub>2</sub> absorption is detected may trace cosmological chemical evolution more reliably since they may comprise a narrower set of physical conditions. The 9 known H<sub>2</sub> absorption systems support this hypothesis: metallicity exhibits a faster, more well-defined evolution with redshift than in the general DLA population. The dust-depletion factor and, particularly, H<sub>2</sub> molecular fraction also show rapid increases with decreasing redshift. We comment on possible observational selection effects which may bias this evolution. Larger samples of H<sub>2</sub>-bearing DLAs are clearly required and may constrain evolution of the UV background and DLA galaxy host type with redshift.

## 1. Introduction

Apart from providing independent supporting evidence of the big bang, the detection and subsequent study of cosmological chemical evolution provides the empirical details of galaxy formation and evolution. How primordial and processed gas is consumed by star formation, the dominant feedback processes and merging scenarios, may all contribute to the overall evolution of chemical abundances. One high-precision probe of this evolution is the spectroscopic study of damped Lyman- $\alpha$  systems (DLAs): absorbers with neutral hydrogen column densities  $N(\text{H I}) \geq 2 \times 10^{20} \text{ cm}^{-1}$ . Although these observations demonstrate that DLAs arise along lines of sight through distant galaxies, they do not directly disclose details such as the galaxy's morphology, luminosity, mass or age.

There exists substantial evidence that DLAs arise in a variety of galaxy types. At low- $z$  ( $z_{\text{abs}} \lesssim 1.5$ ), kinematic and H I 21-cm absorption studies (e.g. Briggs et al. 1985; Briggs, de Bruyn, & Vermeulen 2001) suggest a significant contribution from spiral galaxies, a view supported at high- $z$  by kinematic modelling and abundance studies (Prochaska & Wolfe 1997; Wolfe 2001). How-

ever, direct imaging at low- $z$  (e.g. Le Brun et al. 1997) reveals that DLA hosts are a mix of irregulars, spirals and low surface-brightness galaxies (LSBs). A recent  $z = 0$  H I 21-cm emission study (Ryan-Weber, Webster, & Staveley-Smith 2003) supports this. Boissier (2003) argue that the number of DLAs per redshift interval and the  $N(\text{H}\,\text{I})$  distribution imply that DLAs at  $z < 2$  are a mix of spirals and LSBs whereas, at higher  $z$ , they are more likely to be dwarfs. This is supported by fitting of chemical evolution models to DLA metal abundances (e.g. Baker et al. 2000) and by recent 21-cm absorption searches at high redshift (Kanekar & Chengalur 2003). Though further work is clearly needed, the direct and indirect evidence for a ‘mixed bag’ of DLA hosts is already compelling.

## 2. Selecting a less biased tracer of chemical evolution

Evidence for an increase in DLA metallicities, [M/H], with cosmic time has emerged only gradually (Pettini et al. 1995; Lu et al. 1996; Vladilo et al. 2000; Kulkarni & Fall 2002; Prochaska et al. 2003), the latter reference using over 100 DLAs to provide the strongest statistical evidence so far. Such large samples are required due to the huge scatter ( $\sim 2$  dex) in [M/H] at a given epoch (see Fig. 1), a diversity expected given the variety of DLA hosts discussed above. However, the diversity in [M/H] could also significantly *bias* any estimate of chemical evolution, as could several observational selection effects (e.g. Hou et al. 2001).

In Curran et al. (2003) we suggest that by selecting those DLAs in which H<sub>2</sub> absorption is detected, one may reduce or possibly avoid some of the biases besetting the general DLA population. There are currently 9 confirmed H<sub>2</sub>-bearing DLAs (see below) and, typically, H<sub>2</sub> is detected in only a few velocity components. These H<sub>2</sub>-bearing components seem distinct from the others, showing lower temperatures and higher dust depletion factors [M/Fe] (Petitjean et al. 2002). Therefore, H<sub>2</sub>-bearing DLAs might be a less biased tracer of chemical evolution than the general DLA population since they may allow one to focus on a narrower range of physical conditions throughout cosmic time.

### 2.1. Known H<sub>2</sub>-bearing DLAs

H<sub>2</sub> is detected in DLAs via the Lyman and Werner-band UV absorption lines which generally lie in the H I Lyman- $\alpha$  forest. A compilation of results from H<sub>2</sub> searches in DLAs is given in table 8 of Ledoux, Petitjean, & Srianand (2003, hereafter L03), for which 7 DLAs have confirmed H<sub>2</sub> detections and metallicity measurements: 0013–004 ( $z_{\text{abs}} = 1.973$ ), 0347–3819, 0405–443 ( $z_{\text{abs}} = 2.595$ ), 0528–2505, 0551–366, 1232+082 and 1444+014. The DLA towards 0013–004 (Petitjean, Srianand, & Ledoux 2002) comprises several absorbing components, of which 2 are dominant (their components *c* and *d*):  $N(\text{H}\,\text{I})$  is measured at the mean redshift and we use the mean  $N(\text{H}_2)$  with error given by the range of  $N(\text{H}_2)$  in L03. For the DLA towards 1232+082 we use the  $N(\text{H}_2)$  value and error from Srianand, Petitjean, & Ledoux (2000).

We include two further DLAs: (i) The recent detection towards 0515–4414 (Reimers et al. 2003) and (ii) 0000–2620, regarded as only a tentative detection by L03. However, the H<sub>2</sub> identification has been carefully scrutinised by Levshakov et al. (2000, 2001) and relies on two H<sub>2</sub> absorption features, the L(4-0)R1 and W(2-0)Q(1) lines, the former appearing relatively clean from Lyman- $\alpha$  for-

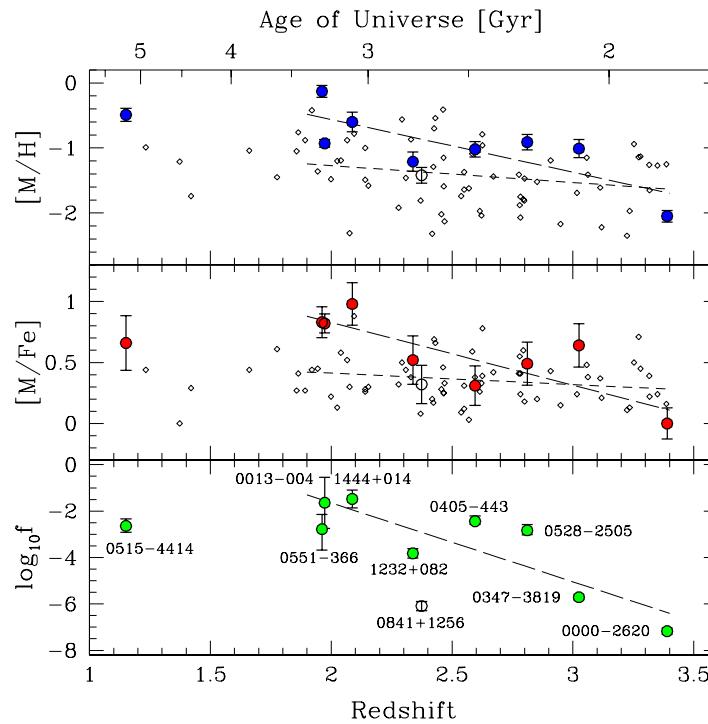


Figure 1. Metallicity [M/H], dust-depletion [M/Fe], and molecular fraction ( $f$ ) evolution for confirmed (filled circles) and tentative (hollow circle) H<sub>2</sub> detections compared with values from the Prochaska et al. (2003) DLAs (small diamonds). The values adopted are discussed in the text. Linear fits to the H<sub>2</sub>-bearing DLAs (long dashes) and general DLAs (short dashes) were obtained by quadrature addition of a constant to the individual error bars such that  $\chi^2_\nu = 1$ . Due to its much lower  $z_{\text{abs}}$  and potentially high photo-dissociation rate (Reimers et al. 2003), we do not include 0515–4414 in these fits (but see Table 1).

est blending. A tentative detection of H<sub>2</sub> in 0841+1256 has also been reported (Petitjean et al. 2000), though confirmation requires future data and analyses.

## 2.2. Results

In Fig. 1 we plot against  $z_{\text{abs}}$  the metallicity [M/H], dust-depletion factor [M/Fe] and molecular fraction  $f \equiv 2N(\text{H}_2)/[N(\text{H}\,\text{I}) + 2N(\text{H}_2)]$  for the 9 H<sub>2</sub>-bearing DLAs, comparing the former two quantities with DLAs in Prochaska et al. (2003) with Zn, Si, S or O metallicity over the relevant redshift range. [M/H] for the H<sub>2</sub>-bearing DLAs is [Zn/H], except for 0347–3819 and 1232+082 where it is [S/H] and [Si/H]. For 0515–4414, [Zn/Fe] is from de la Varga et al. (2000).

The main results from Fig. 1 are summarized by the statistics in Table 1: (i) [M/H], [M/Fe] and  $f$  for the H<sub>2</sub>-bearing DLAs are anti-correlated with  $z_{\text{abs}}$  at the 95% confidence level (i.e. more significant than for the general DLA population), (ii) [M/H] shows a steeper evolution with  $z_{\text{abs}}$  and a smaller scatter

Table 1. Statistics for correlations in Fig. 1.  $P(\tau)$  is the probability of a chance correlation using a Kendall's- $\tau$  test,  $B$  is the slope (with  $1\sigma$  error) of the best fit,  $F$  is the F-test statistic (ratio of variances of two distributions) derived after subtracting the best fits from the data, and  $P(F)$  is the probability that  $F$  could be exceeded by chance alone. Since 0515–4414 is at much lower  $z_{\text{abs}}$  and may have a much higher photo-dissociation rate than the other H<sub>2</sub>-bearing DLAs (Reimers et al. 2003), we present separate statistics for samples excluding and including 0515–4414. Note that this makes little difference.

Sample	H <sub>2</sub> -selected DLAs		'General' DLAs		F-test	
	$P(\tau)$	$B$	$P(\tau)$	$B$	$F$	$P(F)$
<b>[M/H] vs. <math>z_{\text{abs}}</math></b>						
Exc. 0515	0.08	$-0.81 \pm 0.27$	0.14	$-0.26 \pm 0.15$	2.2	0.28
Inc. 0515	0.04	$-0.60 \pm 0.20$	0.03	$-0.26 \pm 0.11$	1.9	0.33
<b>[M/Fe] vs. <math>z_{\text{abs}}</math></b>						
Exc. 0515	0.05	$-0.51 \pm 0.12$	0.24	$-0.09 \pm 0.06$	1.7	0.47
Inc. 0515	0.06	$-0.36 \pm 0.13$	0.25	$-0.07 \pm 0.04$	1.0	0.95
<b>f vs. <math>z_{\text{abs}}</math></b>						
Exc. 0515	0.04	$-3.40 \pm 0.86$	—	—	—	—
Inc. 0515	0.06	$-2.00 \pm 0.75$	—	—	—	—

about the slope than the general DLA population, (iii) [M/Fe] in H<sub>2</sub>-bearing DLAs shows strong evolution with  $z_{\text{abs}}$  while the general DLAs show no evidence for evolution, and (iv)  $f$  ranges over 6 dex and shows a very steep evolution with  $z_{\text{abs}}$ . The new results (i)–(iii) support our hypothesis that H<sub>2</sub>-bearing DLAs form a chemically distinct sub-class and may trace chemical evolution more reliably. The  $f-z_{\text{abs}}$  correlation was studied by L03 and is discussed further below.

The [M/H]s and  $f$ s in Fig. 1 are measured using the total  $N(\text{H}1)$  across the DLA profile and are not specific to the H<sub>2</sub>-bearing components. [M/Fe] is generally found to be uniform across most DLA profiles (Prochaska 2003), indicating that [M/H] should be uniform. However, the H<sub>2</sub>-bearing components typically have much higher [M/Fe] values than other components in the same DLA (e.g. L03 and 0347–383's [Si/Fe] profile in Prochaska 2003). These components usually dominate the non-refractory metal-line profiles and so, although [M/H] and  $f$  will be systematically underestimated, the effect will not be large. The fitted slopes in Fig. 1 are likely to be reasonably robust against this effect, but a larger sample and more detailed study is clearly required.

What observational selection effects and biases could contribute to the steep  $f-z_{\text{abs}}$  evolution? Firstly, the sample is inhomogeneous since the spectra do not all have similar S/N and since the H<sub>2</sub> detection methods and criteria were not uniform. Indeed, the weak H<sub>2</sub> lines detected towards 0000–2620 are at the typical non-detection level (see fig. 16 in L03). The  $f-z_{\text{abs}}$  correlation is therefore only tentative. Secondly, the H<sub>2</sub> detection limit will alter with  $z$ : equivalent widths increase but Lyman- $\alpha$  forest blending worsens with increasing  $z$ . Though this is an unlikely culprit for the 6 dex evolution observed, precise quantification of these competing effects requires numerical simulations. DLAs containing large

amounts of dust could suppress detection of their background quasars and may therefore be ‘missing’ from our sample (Fall, Pei, & McMahon 1989). However, since [M/H], [M/Fe] and  $f$  are positively correlated with each other (e.g. L03), this effect is likely to suppress, rather than create, the correlations in Fig. 1. A recent survey for DLAs towards radio-selected quasars (Ellison et al. 2001) also indicates that the number of such ‘missing’ quasars is likely to be small.

### 3. Interpretations and conclusions

Selecting those DLAs which exhibit H<sub>2</sub> absorption may focus on systems with a narrower range of physical conditions than the DLA population as a whole. Tentative support for this conjecture lies in the steeper, tighter [M/H]– $z_{\text{abs}}$  anti-correlation observed for the H<sub>2</sub> systems studied here. Hou, Boissier, & Prantzos (2001) recently presented detailed chemical evolution models which give a slope for the [M/H]– $z_{\text{abs}}$  relation of  $\sim -0.6$  dex. They correct this result for various observational biases to match the shallower slope observed for the general DLA population. However, the steep [M/H]– $z_{\text{abs}}$  slope observed for H<sub>2</sub>-bearing systems could be less affected by these biases and may avoid those introduced by sampling many different ISM gas phases. It might therefore be more comparable to the uncorrected slopes in the models. H<sub>2</sub>-selected DLAs are therefore a candidate for a less biased probe of chemical evolution.

That there exists such a large range ( $\sim 6$  dex) in the values of  $f$  in Fig. 1 may not be surprising: Schaye (2001) describes a [Zn/H] = –1 photo-ionization model for clouds in local hydrostatic equilibrium. For a representative incident UV background flux and dust-to-metals ratio, the molecular fraction in this model shows a sudden increase of  $\sim 4$  dex for only a small increase in the total hydrogen density. Therefore, the very steep  $f$ – $z_{\text{abs}}$  correlation could be achieved with a modest increase in dust content at lower redshifts, consistent with the observed [M/Fe]– $z_{\text{abs}}$  anti-correlation. L03 also discuss how  $f$  might be very sensitive to local physical conditions. For example, within the Schaye model, one expects an anti-correlation between  $f$  and the intensity of the UV background. However, the behaviour of the UV background flux with redshift over the range  $z = 1$ –3 is still a matter of considerable uncertainty. The strong decrease in  $f$  at high redshift may also be consistent with recent H I 21-cm absorption measurements in DLAs (Kanekar & Chengalur 2003), where a generally higher spin/excitation temperature is found at  $z > 2.5$ . With an increased sample size and more detailed analyses, the  $f$ – $z_{\text{abs}}$  anti-correlation, if real, may provide complementary constraints on these problems.

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